AD-A190 133 ANALYSIS OF VIBRATORY DRIVEN PILE(U) NAVAL CIVIL ENGINEERING LAB PORT HUENEME CA S GARDNER OCT 87 NCEL-N-1779

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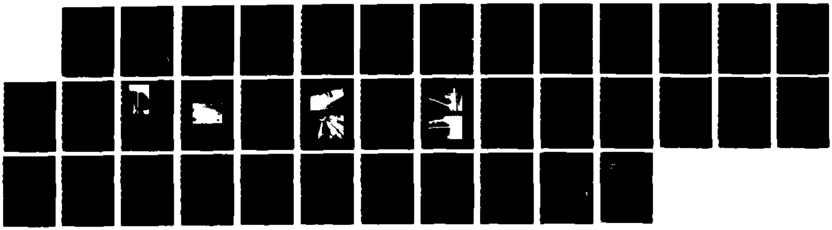

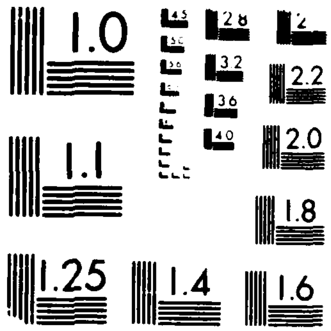
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NCEL
Technical Note

October 1987
By Sherrill Gardner
Sponsored by Naval Facilities
Engineering Command

ANALYSIS OF VIBRATORY DRIVEN PILE

ABSTRACT A vibratory pile driver has the capability of substantially decreasing pile installation time compared to the impact driven pile in certain soil conditions. Despite the increased interest in the use of this type of driver for driving and extraction, no reliable method exists for estimating the pile's bearing capacity. Field tests were conducted in San Diego, California in an effort to compare bearing capacity calculations for vibratory driven pile based on theoretical static analysis, empirical analysis using cone penetrometer test data, and dynamic driving resistance. Data obtained while driving instrumented pile is compared with predictions obtained from an analytical model. This preliminary model simulated the vibratory driver-pile-soil system. This technical note evaluates the influence of various parameters on the vibratory pile driving process.

NAVAL CIVIL ENGINEERING LABORATORY PORT HUENEME CALIFORNIA 93043

METRIC CONVERSION FACTORS

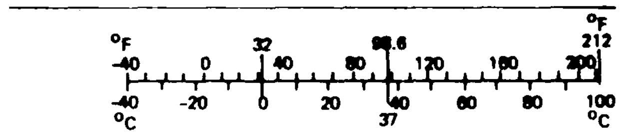
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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A vibratory pile driver has the capability of substantially decreasing pile installation time compared to the impact driven pile in certain soil conditions. Despite the increased interest in the use of this type of driver for driving and extraction, no reliable method exists for estimating the pile's bearing capacity. Field tests were conducted in San Diego, California in an effort to compare bearing capacity calculations for vibratory driven pile based on

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theoretical static analysis, empirical analysis using cone penetrometer test data, and dynamic driving resistance. Data obtained while driving instrumented pile is compared with predictions obtained from an analytical model. This preliminary model simulated the vibratory driver-pile-soil system. This technical note evaluates the influence of various parameters on the vibratory pile driving process.

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A vibratory pile driver has the capability of substantially decreasing pile installation time compared to the impact driven pile in certain soil conditions. Despite the increased interest in the use of this type of driver for driving and extraction, no reliable method exists for estimating the pile's bearing capacity. Field tests were conducted in San Diego, California in an effort to compare bearing capacity calculations for vibratory driven pile based on theoretical static analysis, empirical analysis using cone penetrometer test data, and dynamic driving resistance. Data obtained while driving instrumented pile is compared with predictions obtained from an analytical model. This preliminary model simulated the vibratory driver-pile-soil system. This technical note evaluates the influence of various parameters on the vibratory pile driving process.

CONTENTS

INTRODUCTION

Vibratory drivers have been used since the 1930s to drive and extract piles. Vibratory pile drivers have the capability of significantly decreasing pile installation time, especially in granular soils. However, they have not been widely accepted because of the uncertainty in estimating the bearing capacity of the driven pile. When driving bearing piles, the standard industry method for obtaining load carrying capacity of a pile installed with a vibratory driver is to redrive with an impact hammer. The advantage of improved productivity is lost with the redrive procedure. Currently, there is no other method to predict the capacity of these bearing piles installed with a vibratory driver. The Naval Civil Engineering Laboratory (NCEL) is making progress toward being able to estimate the bearing capacity of these piles.

This technical note describes field testing and corresponding analytical modeling of the vibratory driver-pile-soil system. The following sections describe the development of the numerical model and techniques for collecting field data. A discussion of the prediction of the pile driving process based on field test data is followed by suggestions as to the additional work that should be done to further verify the model to a point where it can be used with confidence.

BACKGROUND

The Navy uses temporary pier facilities to transfer cargo over the surf to the beach during amphibious operations. Pile driving is the most time consuming activity during construction of these facilities. The Amphibious Construction Battalions (PHIBCBs) use single-acting diesel hammers to install these piles. A vibratory driver is used to extract the pile during the retrieval phase. Because they cannot rely on the vibratory driver to drive piles to a specific bearing capacity, two pieces of equipment are necessary to handle pile installation and extraction. A more efficient technique, such as using the vibratory driver to both install and extract bearing piles, would both eliminate the requirement for having two pieces of equipment to handle piles and also improve pile installation rates.

The Mobile Construction Battalions (MCBs) have double-acting air hammers (MKT7) and single-acting diesel hammers (MKT DE20/30). They do a wide variety of pile driving work related to waterfront and advance base construction. A vibratory pile driving capacity could improve their operational capability.

MODELING THE VIBRATORY PILE DRIVING PROCESS

Vibratory Drivers

Vibratory drivers apply a dynamic force to the pile from paired rotating weights which are set eccentric to the center of rotation so that when they rotate, their vertical forces are added and the horizontal forces canceled. The frequency at which these drivers operate is in the range of 18 cps to 33 cps. This frequency range produces a ground resonance at which shear and frictional resistance of the soil are significantly reduced (Ref 1). Vibratory driving appears to work well in coarse-grained soils and with nondisplacement piles (Ref 2). In sand, it is thought that the vibrated piles may have much higher bearing values than driven piles because of the compacting effect of the vibration (Ref 3).

In order to improve the driving effectiveness of vibratory drivers, a sizeable "suspended" weight is usually added to the nonvibrating portion of the driver. In some cases, additional static force is applied to the top of the driver, for example, through the jib to push-drive the pile.

Another use of the vibratory driver is in extraction of piles. In this case, tension is applied through the jib of the crane. Occasionally, a shock absorber will also be used to reduce the vibrations from the driver to the boom. Vibratory drivers also allow reduced noise during pile driving operations, controlled depth of penetration, the ability to drive piles at inclinations of 1:1 or more, and underwater driving. Schematic drawings of the vibratory driver as used in the different applications are shown in Figure 1.

A resonant (sonic) vibratory driver, designed by the Bodine Soundrive Company of California, has a variable frequency capability within the sonic range of frequencies up to and over 100 Hz. This allows the pile to be installed at its resonant frequency. The impulse of the vibration is in phase with the elastic compression wave that travels down the pile, and the energy is used most effectively in overcoming friction and point resistance (Ref 4). This significantly increases the pile movement. In a comparison study using two identical piles at the same site, a steam hammer sank a pile 67 feet in 90 minutes while the sonic hammer sank the pile 71 feet in 42 seconds. This driver is still in the development stage and is not available for commercial use at this time.

Generally, the loss of energy in the vibratory driver is considerably less than that in a conventional hammer. In the latter, much of the energy of the impact is dissipated in compressing the cushion blocks and driving head, and in overcoming the skin friction that may possibly develop between widely spaced blows.

The Wave Equation Analysis

Since the middle 1800s, dynamic pile-driving formulas have been used to determine the static bearing capacity of piles as a function of the resistance of the pile to penetration. At the present time, several hundred such pile-driving formulas exist. These formulas are usually

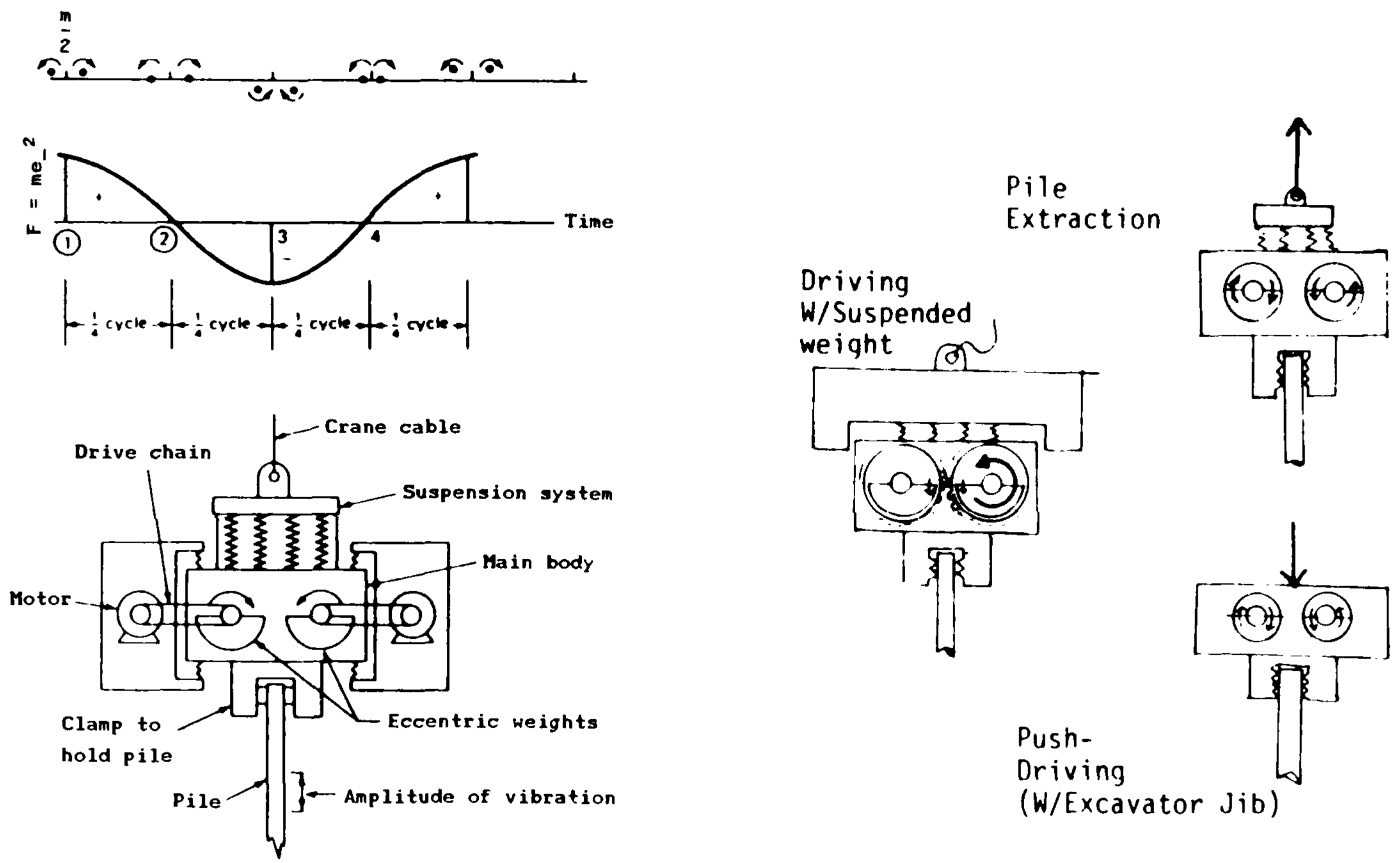


Figure 1. Schematic drawing of a vibratory driver.

obtained by equating the energy delivered to a pile to the distance the pile moves against a soil resistance. The results are not always reliable, and may over-predict or grossly under-predict pile capacities, and therefore should be used with caution.

Dynamic resistance based on the wave equation analysis is a more rational approach to calculating pile capacities. This method was first put into practical form in 1962 by Smith (Ref 5). Results of the wave equation analysis can be interpreted to give pile stress, the rate of penetration, and the driving resistance.

The wave equation was later written into computer codes and the descriptions and documentations can be found in numerous publications (Ref 6 through 10). For the impact hammer, the computer code will solve for the idealized system shown in Figure 2.

The VIBEWAVE Program

The original form of the Texas Transportation Institute (TTI) wave equation analysis program (Ref 10) is used to model pile driving using the vibratory driver. Numerous modifications were required. The first modification was to model the idealized vibratory driver-soil-pile system shown in Figure 3.

As can be seen in Figure 3, the first element is the "suspended weight." It transmits its weight, W_1, and inertia force to the second element called the "driver" through an "isolation spring." The isolation spring has stiffness K_1. The dead weight of the driver excludes the rotating weights and gears, but includes the rest of the assembly as well as the "head" or clamp which is to be fastened to the first pile element. In the program, the mass of the rotating weights and gears, m (total eccentric mass); the eccentricity, e; and the frequency, f (in cycles per second, cps) are input separately.

The oscillatory vertical driving force imparted by the "driver" has a maximum value:

$$P_{max} = m(a + e\,w^2)$$

where: m = mass of rotating weights and gears (total eccentric mass)

a = acceleration which is calculated from the change in velocity of the eccentric mass between time steps

e = eccentricity

w = angular velocity (in radians per second) which is related to the frequency, f, by $2\pi f$

f = frequency in cycles per second (cps)

The driving force varies sinusoidally with time, t, and is given as a function of t:

$$P(t) = m\,a + m\,e\,w^2 \sin wt$$

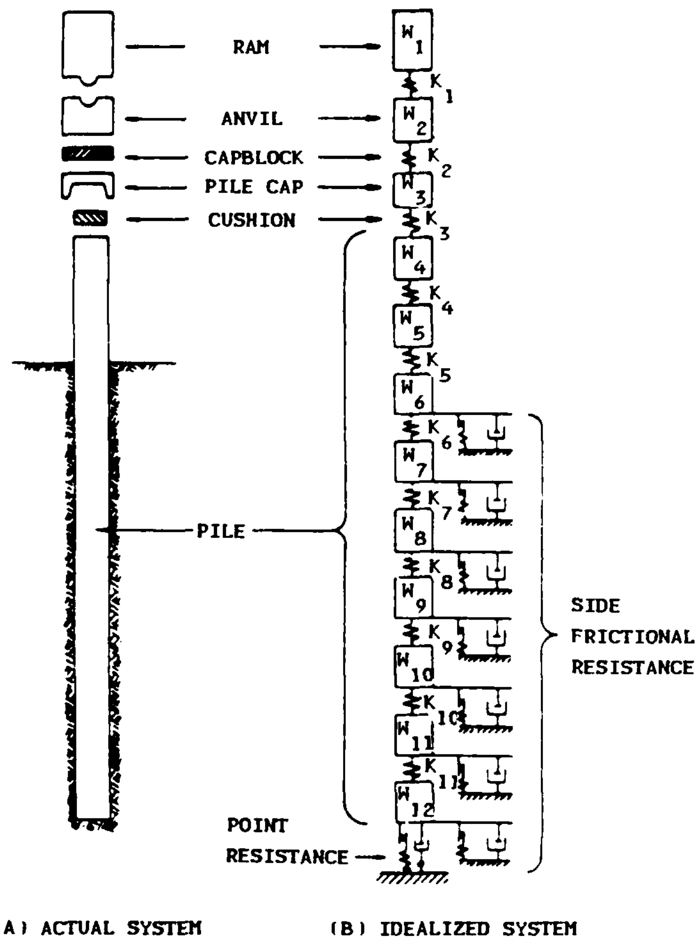


Figure 2. Simulation of an impact hammer-pile-soil system.

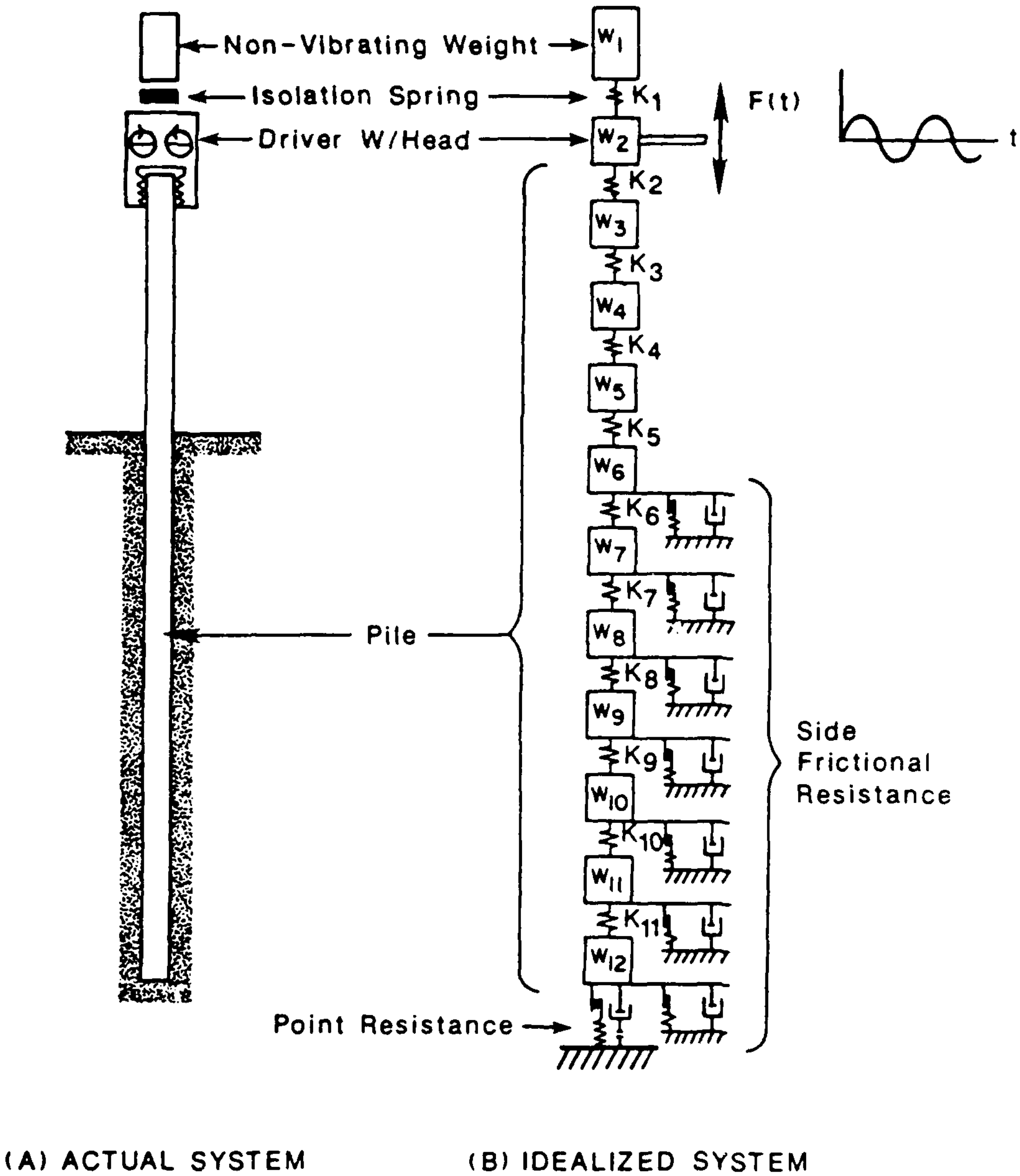


Figure 3. Simulation of a vibratory driver-pile-soil system.

Several minor changes are also made to the original program to reinitialize certain values for the vibratory driven pile.

Predictions from the VIBEWAVE program are compared with the results of instrumented pile driving tests performed by NCEL in Coronado, California.

DESCRIPTION OF FIELD TESTING

Cone Penetrometer Test (CPT)

The CPT was considered the appropriate technique for this test due to the short lead time available for site investigation. Relative to other soil exploration methods, the CPT provides faster, more detailed data. However, it has the distinct disadvantage of not obtaining a soil sample for visual or lab inspection.

Nine cone penetrometer test drillings were conducted for a total of 203 feet. The drillings were located on a grid established on the beach at the Naval Amphibious Base in Coronado, California. The area was approximately 150 yards measured inland from high water by 600 yards measured parallel to the beach. Minimum depth to refusal was 7 feet in two holes. Maximum depth to refusal was 30 feet. Continuous readings of tip bearing, sleeve friction, and pore pressure were obtained with depth. Interpreted information such as soil behavior type, equivalent Standard Penetrometer Test (SPT) N values, D50, equivalent drained friction angle, and equivalent relative density was also provided.

The soil at the test site consisted mainly of very dense sand with an average unit weight of about 127 pcf. On land, the water table was at about 8 feet to 10 feet below ground level. The angle of frictional resistance of the sand as interpreted from the cone penetration data was about 45 degrees. A pile capacity curve was developed for the 8-5/8-inch-diameter pile, assuming the pile plugs after penetrating three diameters. Typical cone penetration test data and the corresponding pile capacity curve is shown in Figures 4 and 5, respectively.

Rate of Pile Penetration Versus Dynamic Driving Resistance

The ultimate capacity of a pile can be estimated from the penetration per blow when using an impact hammer. Formulas for dynamic driving resistance are outlined in Reference 7. The use of this method should be supported by local experience or testing.

The first phase of tests were designed to demonstrate a relationship between rate of penetration and dynamic driving resistance. A Foster Vibro 1000 was used to drive a 20-inch-diameter pipe pile for 4 feet. The rate of penetration was recorded for the 4-foot increment. Dynamic driving resistance was recorded by removing the vibratory driver and counting the number of blows for the next foot of penetration with an MKT DE-30 diesel impact hammer. The vibratory driver was then placed back on the pile and driving was continued for another 4 feet and so on (Figure 6).

Rates of penetration for the first 9 feet ranged from about 3 ft/min to 5 ft/min after which the rates dropped sharply to less than 0.5 ft/min.

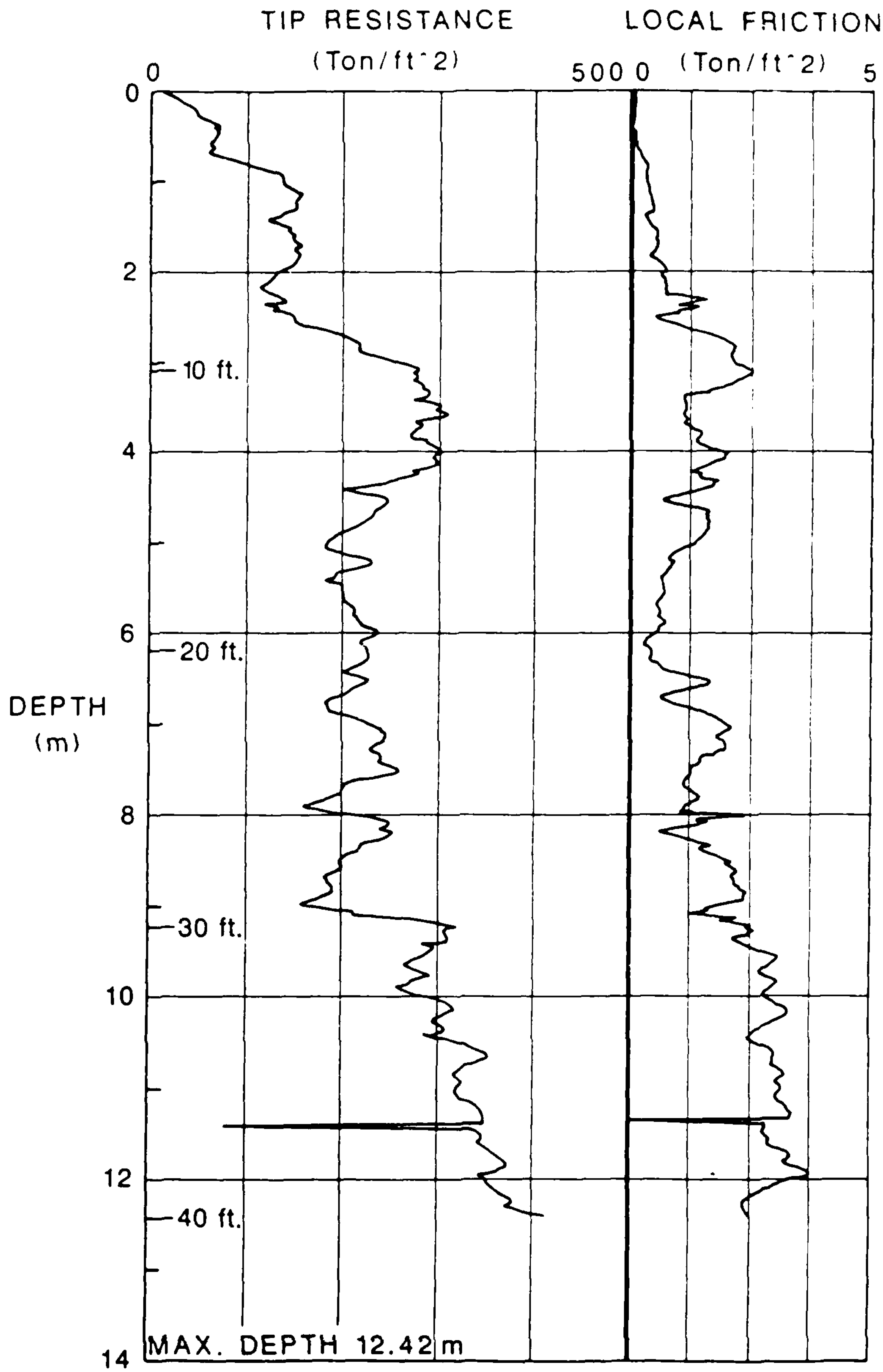


Figure 4. Typical CPT data at the test site.

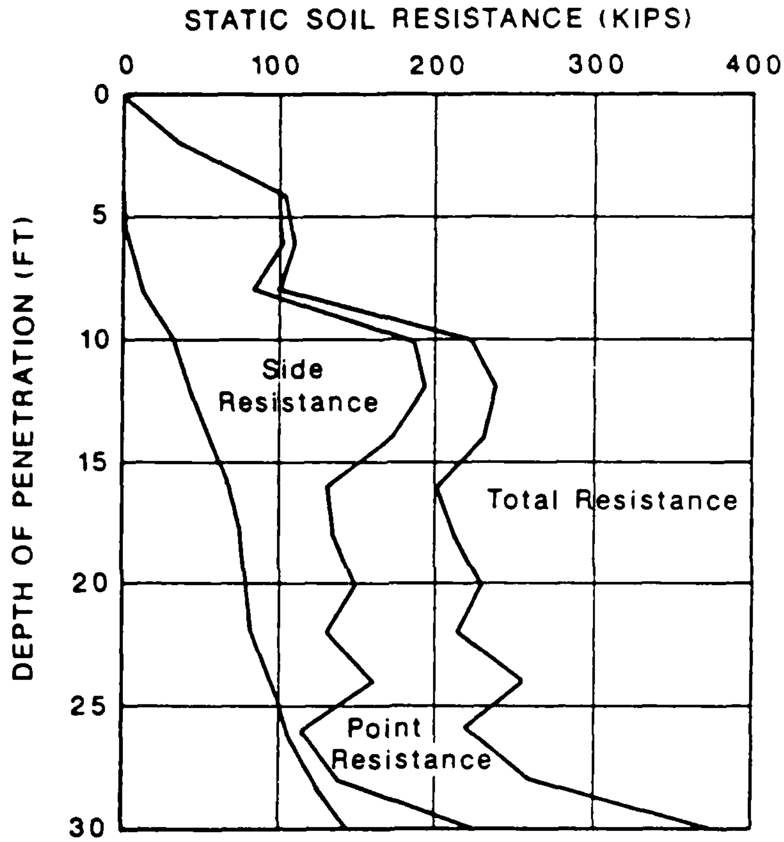


Figure 5. Pile capacity curve for an 8-5/8-inch-diameter pile at the test site.

Figure 6. 20-inch diameter pile driven by Foster Vibro 1000 (DE30 diesel hammer on left).

The data collected are summarized in Table 1. The maximum penetration that the pile was able to attain with the Vibro 1000 ranged from 10 to 13 feet. This was attributed to the extremely dense soil conditions.

Table 1. Observed Rate of Penetration Versus Dynamic Driving Resistance

Pile[a]	Depth (ft)	Rate of Penetration[b] (ft/min)	Blow Count[c] (blws/ft)	Bearing Capacity[d] (tons)
1	5-9	2.9	30	35
	10-11.5	0.3	36	40
2	5-9	5.1	25	31
	10-11.5	0.2	45	48
3	5-9	4.6	22	29
	10-12.8	0.3	40	44
	13.8-14	0.03	48	53
4	5-13	1.2	40	44

[a] 20"ϕ x 1/2" WT, open-end, steel pipe pile (ϕ = outside diam.; WT = wall thickness).
[b] Average rate for depth indicated; using Foster Vibro 1000 driver.
[c] MKT DE30 diesel hammer.
[d] Engineering News Formula.

Instrumentation

The next phase of tests required instrumenting the pipe pile with strain gages to record data during driving. Anticipating that a smaller diameter pile could be driven to a depth of 25 to 30 feet with the vibratory pile driver, it was decided to use 8-5/8-inch-diameter pipe pile (a size readily available). An adapter was designed and fabricated to allow driving the smaller diameter pile with both of the pile drivers that are set up to drive 20-inch-diameter pipe piles (Figure 7). This section describes the procedures used to collect dynamic data.

Figure 7. Pile adapter.

The selected piles were sandblasted in preparation for applying the instrumentation. Four SG-129 Ailteck weldable strain gages were positioned around the pile 2 feet from the top (Figure 8) to function as a load cell. Additional gages were positioned along the length of the pile in 5-foot increments (Figure 9). This arrangement allowed the force delivered to the pile and force attenuation along the length of the pile to be measured during driving.

Once the gages along the length of the pile were in place and the leads secured with tape, 1/8-inch steel angle was placed over the gages and leads and tack welded to the pile. The angle was put on in 5-foot pieces to insure stresses were not being transferred to the pile through the angle. The end of the angle near the pile butt was closed off to prevent soil intrusion. The gages and leads at the top of the pile were secured firmly with tape and metal bands (Figure 9).

Thermocouples were installed, after-the-fact, to give an indication of the temperature variations when the pile heated up significantly during the vibratory pile driving process. These gages were placed along the same spacing as the strain gages and covered with PVC pipe. The PVC pipe was not able to withstand the rigors of the vibratory pile driving or the heat generated due to the driving. For future testing, the thermocouples would also be placed under the protective covering of steel angle.

Dynamic Driving Data

An instrumented pile was fitted with a pointed tip and an adapter (Figure 10). Refusal was met consistently at 11 to 12 feet. Rates of penetration and corresponding dynamic driving data from the strain gages were recorded for three separate driving attempts. The observed rates of penetration versus depth are shown in Table 2. The tests were concluded with the Vibro 1000.

Table 2. Comparative Rates of Penetration for Pipe Pile Driven With Foster Vibro 1000 Driver

Depth[a] (ft)	Rate of Penetration[b] (ft/min)		
	No. 1	No. 2	No. 3
1-4	-	-	-
4-5	-	-	5.0
5-6	0.4	2.3	-
6-7	0.7	2.3	-
7-8	0.7	2.0	-
8-9	0.7	2.0	-
9-10	0.1	-	1.0
10-11	-	0.3	-
11-12	-	0.1	0.1
12-12.5	-	0.1	-

[a] 8-5/8"ϕ, 3/8" WT, closed-end steel pipe pile; 20-ft length.
[b] Rates averaged over depth indicated.

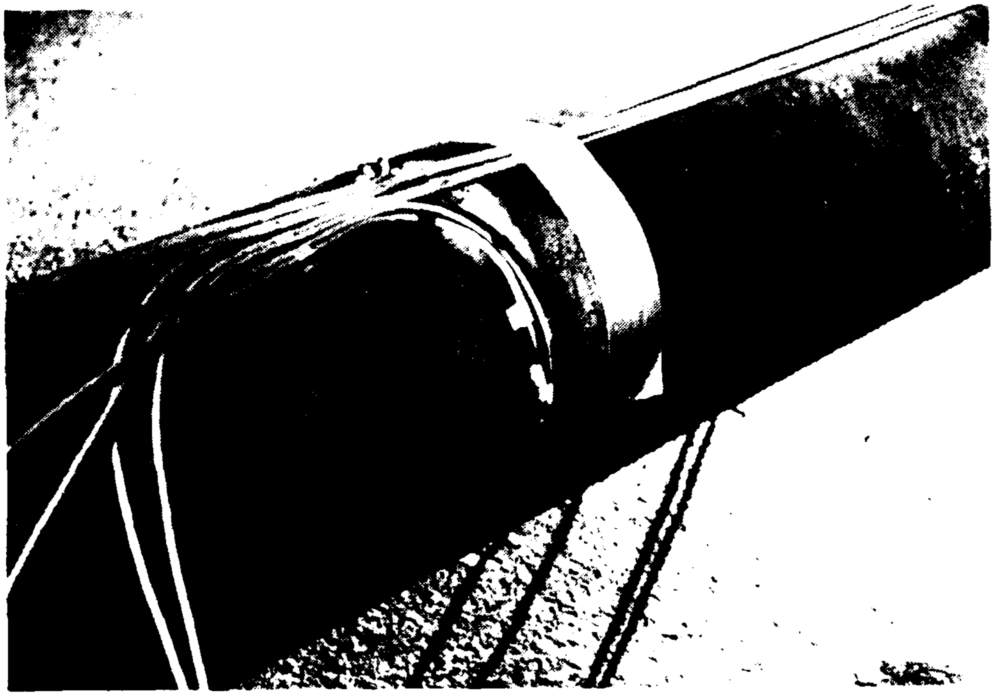


Figure 8. Strain gages near pile top.

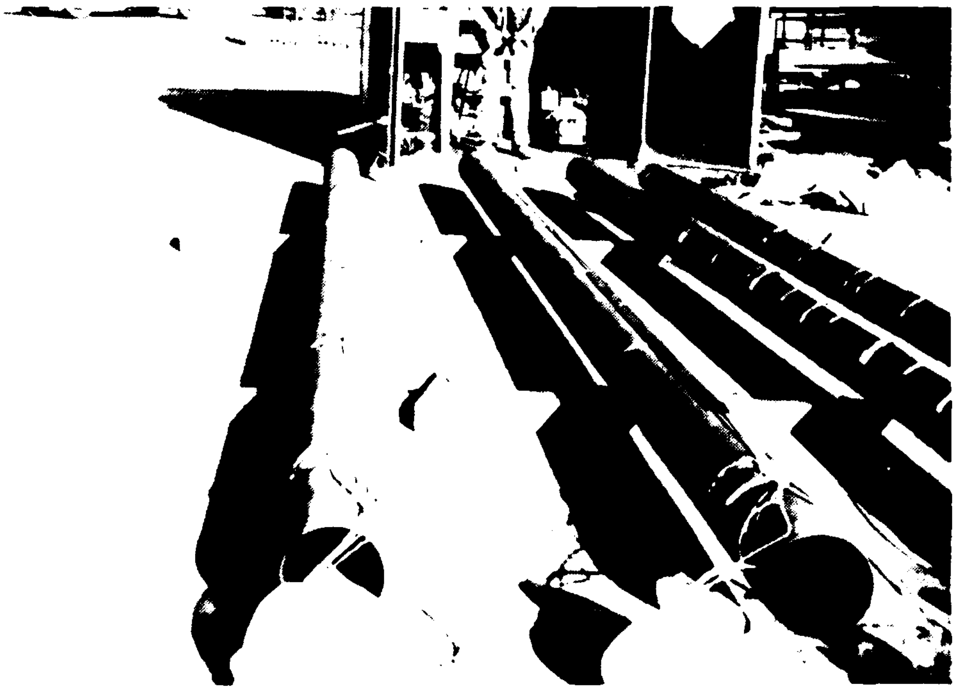


Figure 9. Strain gages positioned along length of pile (steel angle is being placed on second pile from left).

There was an opportunity a few months later for further testing in the same test area and in the surf near the test area. A Foster Vibro 1800 was used to drive an 8-5/8-inch-diameter open-end pipe pile. One of the objectives of these tests was to verify whether a bigger driver would be able to penetrate the dense cobble layer encountered in previous tests. The Vibro 1800 is rated at 65 tons driving force compared with the 35 tons driving force of the Vibro 1000. We also wanted to obtain dynamic driving data while driving in saturated soil conditions. An 8-5/8-inch-diameter instrumented pile was driven off the side of a roadway section of the Elevated Causeway (ELCAS) which had been deployed at the Naval Amphibious Base Coronado, California (Figure 11). This beach is in the same general area as the test area.

Rates of penetration were recorded simultaneously with the strain gage and thermocouple data. The depth to refusal on the beach was 23 feet. Maximum depth to refusal in the surf was 12 feet after three separate attempts of driving in approximately 3 to 5 feet of water. In order to keep the pile upright in the first few feet of driving, the crane had to keep tension on the driver until the pile was sufficiently set in the ground. This affected the rates of penetration. Observed rates of penetration versus depth are shown in Table 3. Strain gage readings are shown in Figure 12. Comparable strain gage plots are not available for the first set of tests.

Table 3. Comparative Rates of Penetration for Pipe Piles Driven With Foster Vibro 1800 Driver

Depth[a] (ft)	Rate of Penetration[b] (ft/min)			
	No. 1[c] (beach)	No. 2 (surf)	No. 3 (surf)	No. 4 (surf)
1-2	-	-	-	-
2-4	-	4.8	0.8	1.3
4-6	-	1.8	0.8	1.3
6-7	-	0.3	0.8	-
7-8	3.8	0.3	0.8	-
8-9	4.0	0.7	0.8	-
9-10	2.6	0.7	-	-
10-11	1.4	0.8	-	-
11-12	0.7	0.8	-	-
12-13	0.8	-	-	-
13-14	0.5	-	-	-
14-15	0.4	-	-	-
15-16	0.5	-	-	-
16-17	0.3	-	-	-
17-18	0.3	-	-	-
18-19	0.5	-	-	-
19-20	0.3	-	-	-
20-21	0.2	-	-	-
21-22	0.1	-	-	-

[a] 8-5/8"ϕ, 3/8" WT, open-end pile; 30-ft length.
[b] Rates averaged over depth indicated.
[c] Test results compared with predictions from VIBEWAVE program.

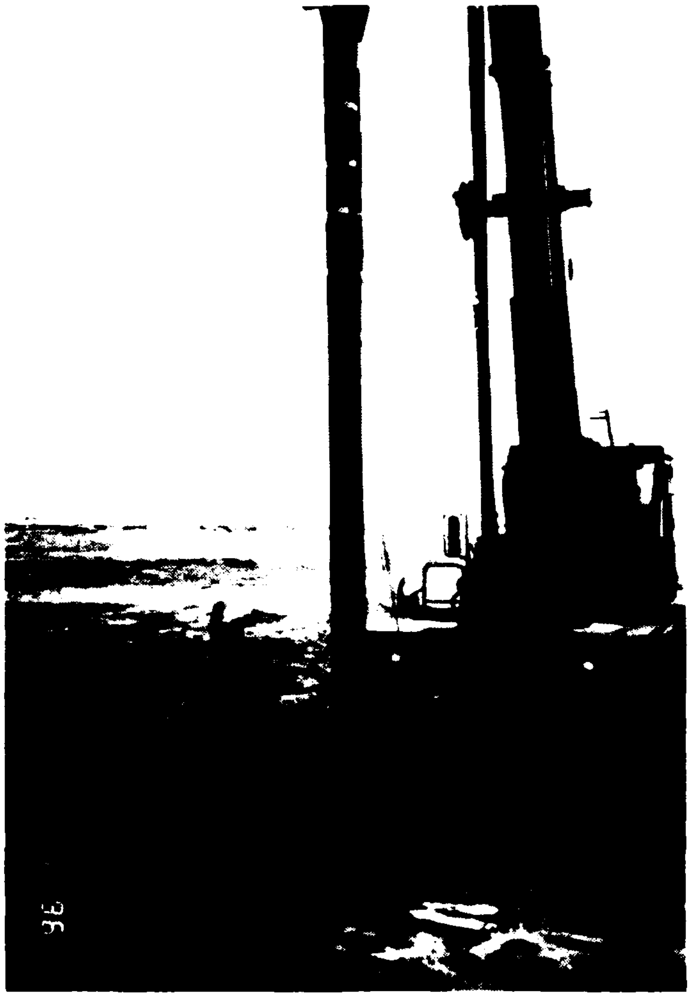


Figure 10. Instrumented 8-5/8-inch-diameter pile fitted with tip and adapter.

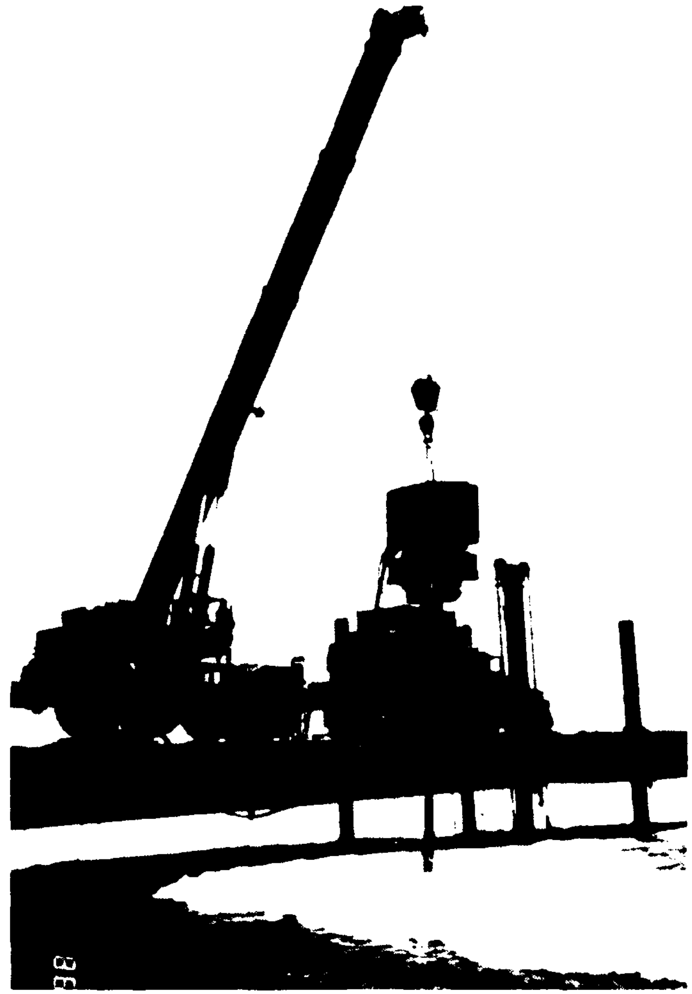


Figure 11. Instrumented 8-5/8-inch-diameter pile driven off side of ELCAS roadway.

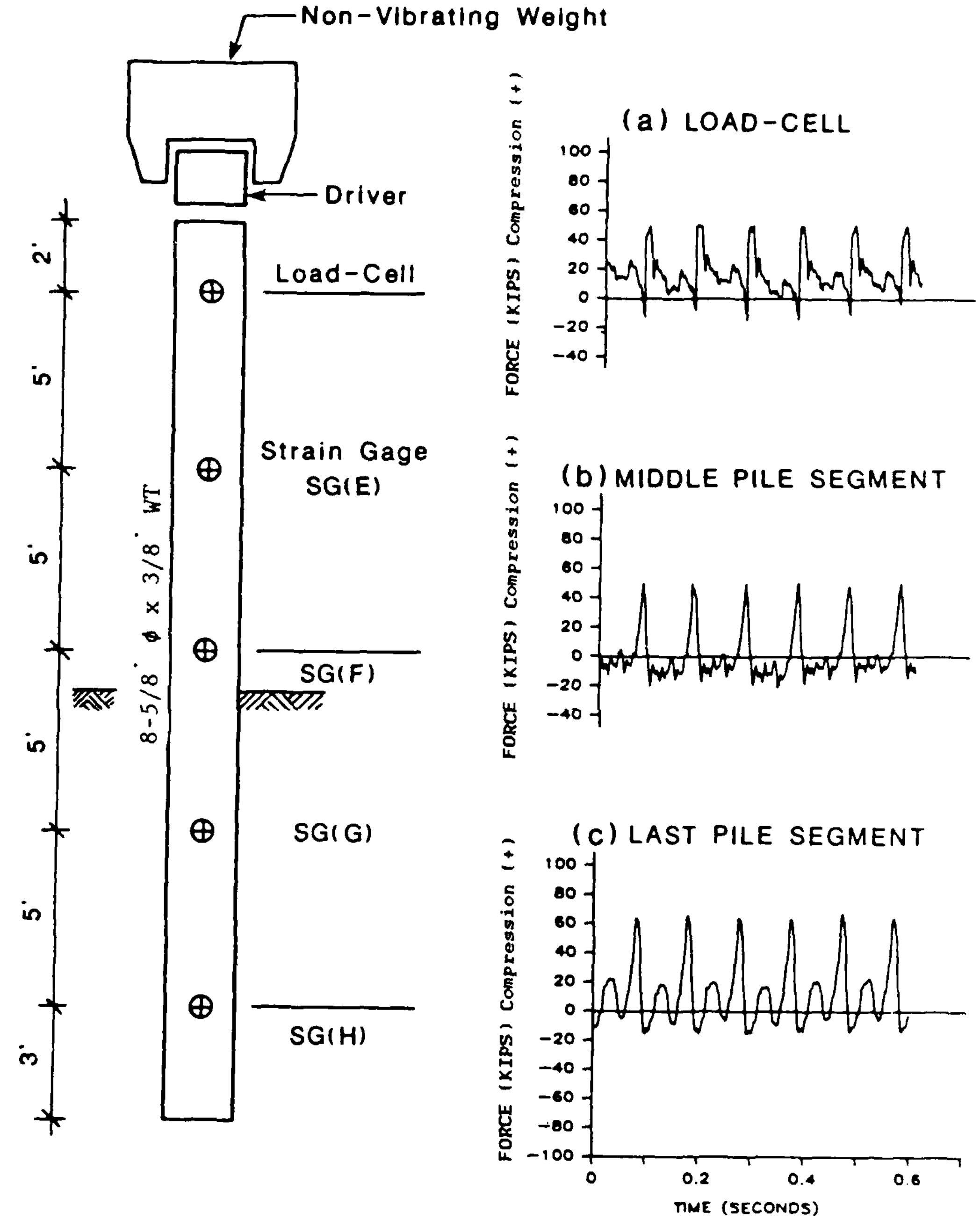


Figure 12. Strain gage placement and recorded force histories for an 8-5/8-inch-diameter test pile.

Although the thermocouples were lost due to inadequate protection, temperatures ranging from 400 to 500°F were recorded at the tip of the pile by the time refusal was met.

COMPARISON OF MODEL PREDICTIONS WITH TEST DATA

Modeling the Test Piles

In the VIBEWAVE model runs, the 8-5/8-inch-diameter by 5/16-inch WT (wall thickness) steel pipe pile was divided into 5-foot-long segments. The results that will be discussed in the following sections are for the pile driven with the Vibro 1800.

The weight of each rotating/vibratory element consists of an eccentric gear with an eccentric weight of 217 pounds. There are four such elements in the Vibro 1800. From the rated eccentric moment given for each hammer, the rotating arm or eccentricity was estimated to be about 2.1 inches. Although the driving frequencies of the vibratory driver were rated to be 1,000 to 1,600 cycles per minute (about 17 to 27 cps), only about 1,100 cpm (18 cps) was noted during driving. The isolation springs, which are sets of shear springs supporting the nonvibrating weight, have a spring constant of 14 kips/in for the Vibro 1800.

The calculated forces for the idealized vibratory driver-soil-pile system are shown in Figure 13. A compressive force is presented as a positive value. The depth of penetration considered in both cases is about 11 feet. This corresponds to about 180 seconds of driving in the field. The calculated forces and displacements are for the soil-pile system starting from the at-rest position.

The following sections discuss and compare the VIBEWAVE predictions with results from the pile driven on the beach in Table 3, referred to in this report as Test Pile 86.

Driving Forces

The Vibro 1800 driver is rated to give a maximum driving force of 65 tons. (The maximum driving force refers to the amplitude, which is the crest to trough value of the force imparted by the oscillatory weights and gears to the pile.) The results from the VIBEWAVE runs show the maximum driving force to be within that range (Figure 13a).

Forces in the Pile

The load-cell in the 25-foot-long pile is located 2 feet below the pile head. Four other gages were spaced at 5-foot intervals from the load cell. The readings from the strain gages (recorded in microstrain) were converted to forces, in kips, by multiplying by the elastic modulus of steel and the cross-sectional area at the gage location (8.4 in^2).

Recorded force histories for Test Pile 86 are shown in Figure 12. This is typical for most of the piles tested. From Figure 12a, for the case of the test pile driven on land at an 11-foot depth of penetration, the maximum amplitude of the force measured at the load cell is between -20 and 80 kips. A comparison of the forces recorded at each strain gage indicates a consistent stress wave propagating along the pile.

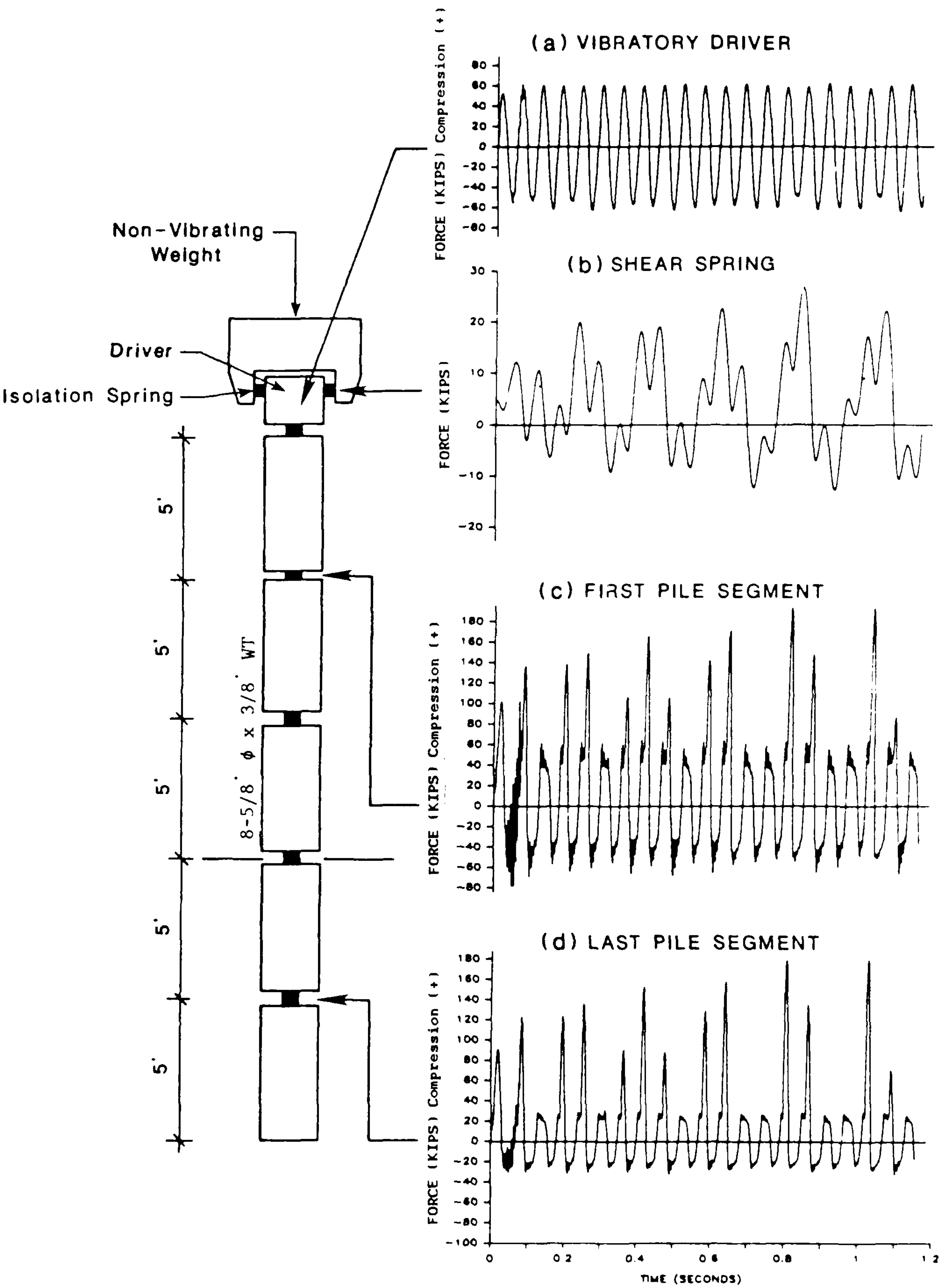


Figure 13. Calculated force histories for an 8-5/8-inch-diameter test pile.

In comparing the magnitude of the calculated and recorded forces at the top of the pile (Figure 14), the recorded is smaller. Any number of factors could account for the discrepancies, including driver performance, instrumentation performance, or the accuracy of the computer model. It is interesting to note that only one or two of every four load cycles imparted to the system show up distinctly in the recorded waveform. This is due to the wave reflecting back up the pile, interfering with subsequent waves traveling down. From a parametric study described below, it appears that the waveform can also be changed by varying the stiffness of the isolation spring.

When the calculated and recorded forces near the tip of the pile (Figure 15) are compared, the calculated forces are again larger. More damping is probably occurring in the field than expected. Note the similarity in waveforms between the calculated and recorded force histories.

Note the relative differences in the magnitude of the force between pile top and pile tip. The force in the last pile segment is smaller than that at the top for the calculated results. This is due to the skin resistance which was applied on the embedded segments of the pile. This reduction is not apparent in the recorded results. The model does not as yet account for the significant reduction in side friction that occurs during driving.

Rate of Penetration

The predicted penetration rate is obtained from Figure 16 which shows the displacement-history of the pile point. The rate of penetration is about 0.81 in/sec or about 4 ft/min. This compares favorably with the range of 4 ft/min to 1.4 ft/min recorded for the penetration depth of 9 to 11 feet (see Table 3). Although the results look promising, it is hoped that this predictive method can be further improved using information obtained from piles driven to a greater depth using the vibratory driver.

From a parametric study, it appears that some values of the isolation spring stiffness can be determined to give a good prediction of penetration rate for the pile at this site. It can be expected that this value will change with different natural frequencies of different hammer-soil-pile systems.

Behavior of the Isolation Spring

As described earlier, the isolation spring is made up of a set of elastomeric shear springs which has a tendency to soften at higher temperatures. In practice, it is not uncommon for the elastomer to fail while driving. This failure (of the isolation spring and hence the vibratory driver) can be caused by underestimating: (a) the effects of temperature, and/or (b) the magnitude of the dynamic force that can be induced while driving. Although field verification is not yet available, it appears that VIBEWAVE can estimate the latter as seen in Figure 13b. Parametric studies have shown that for a spring stiffness of less than 10 kips/in the elastomer is always in compression. The displacement experienced by the isolation spring is shown in Figure 17.

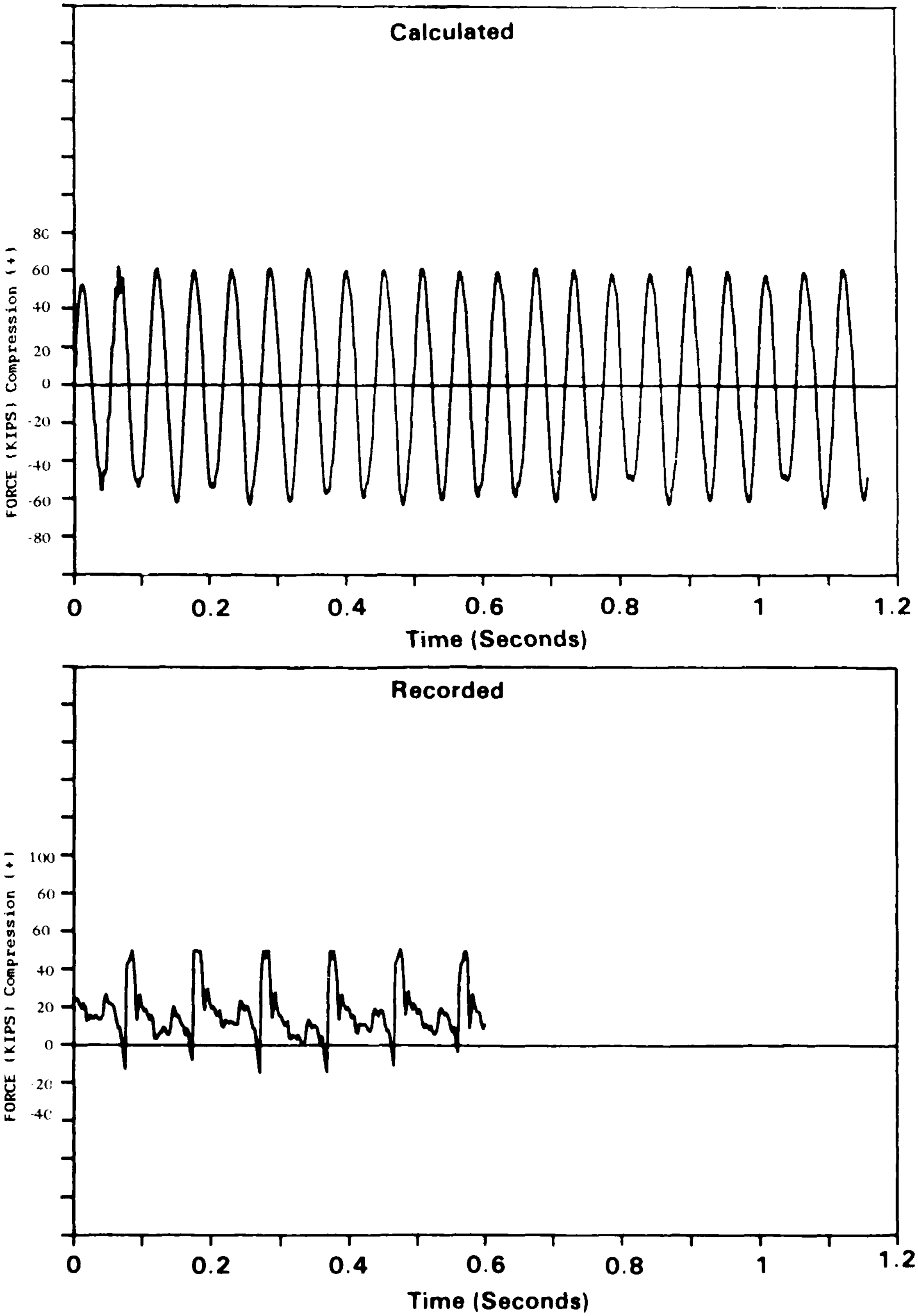
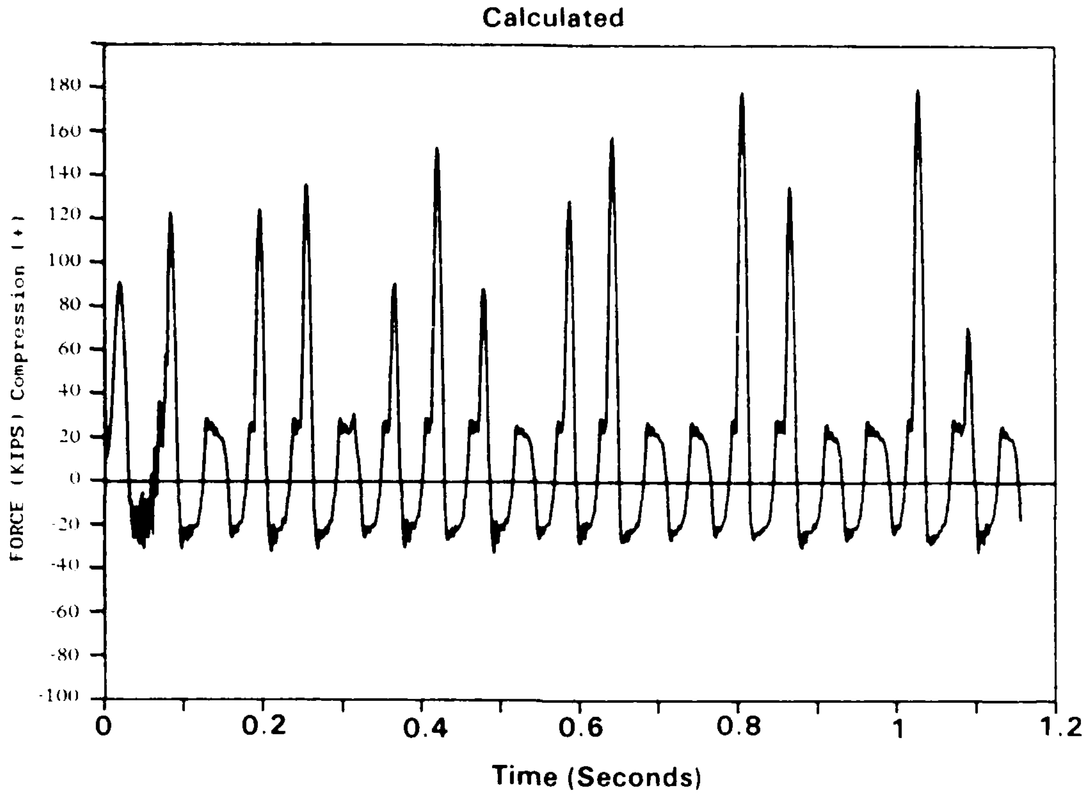


Figure 14. Comparison of force histories at top of pile.



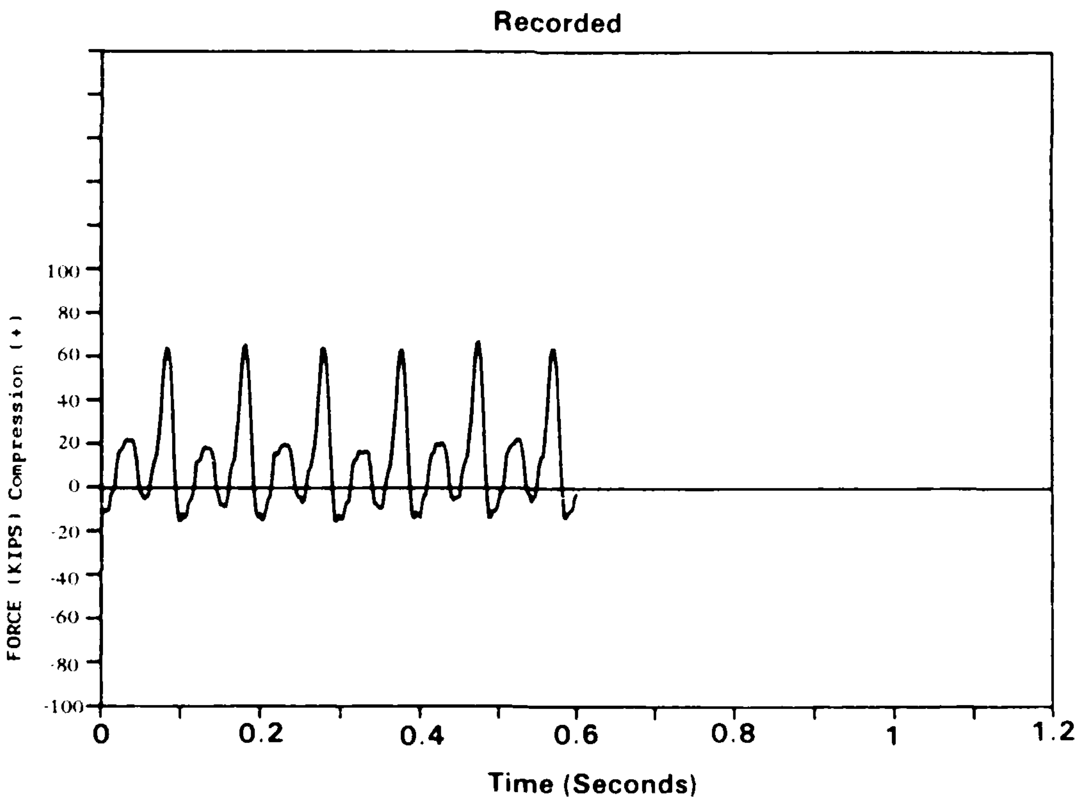


Figure 15. Comparison of force histories near pile tip.

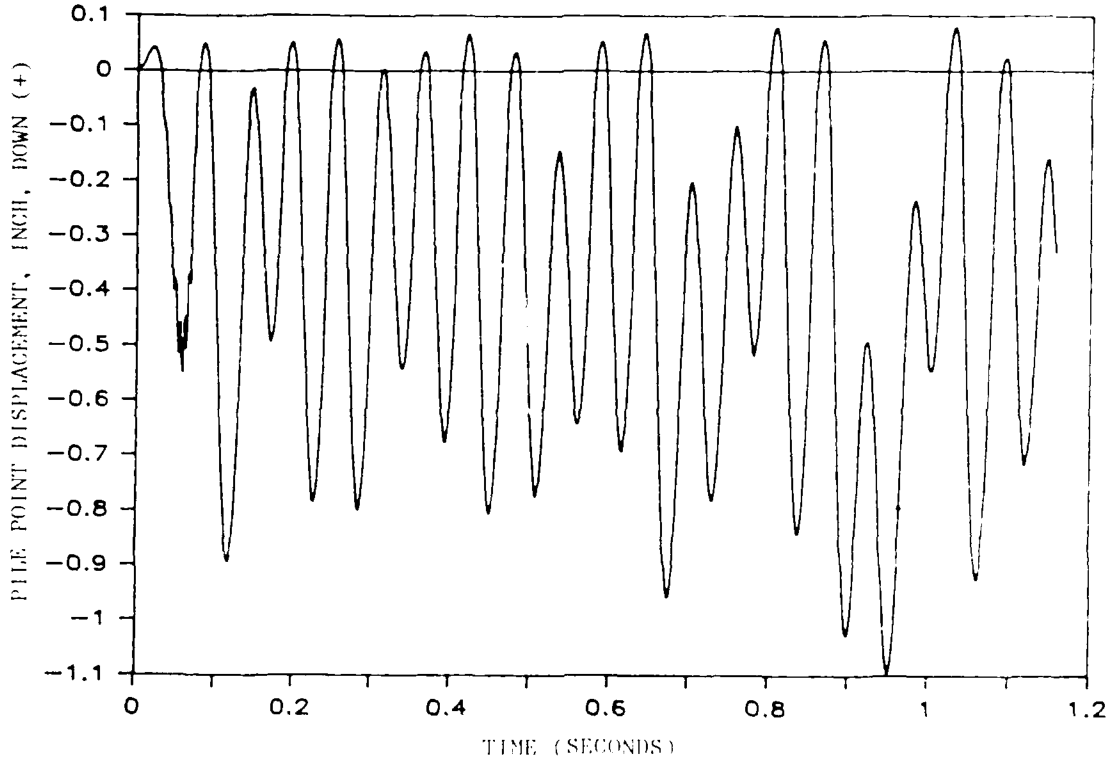


Figure 16. Pile point displacement.

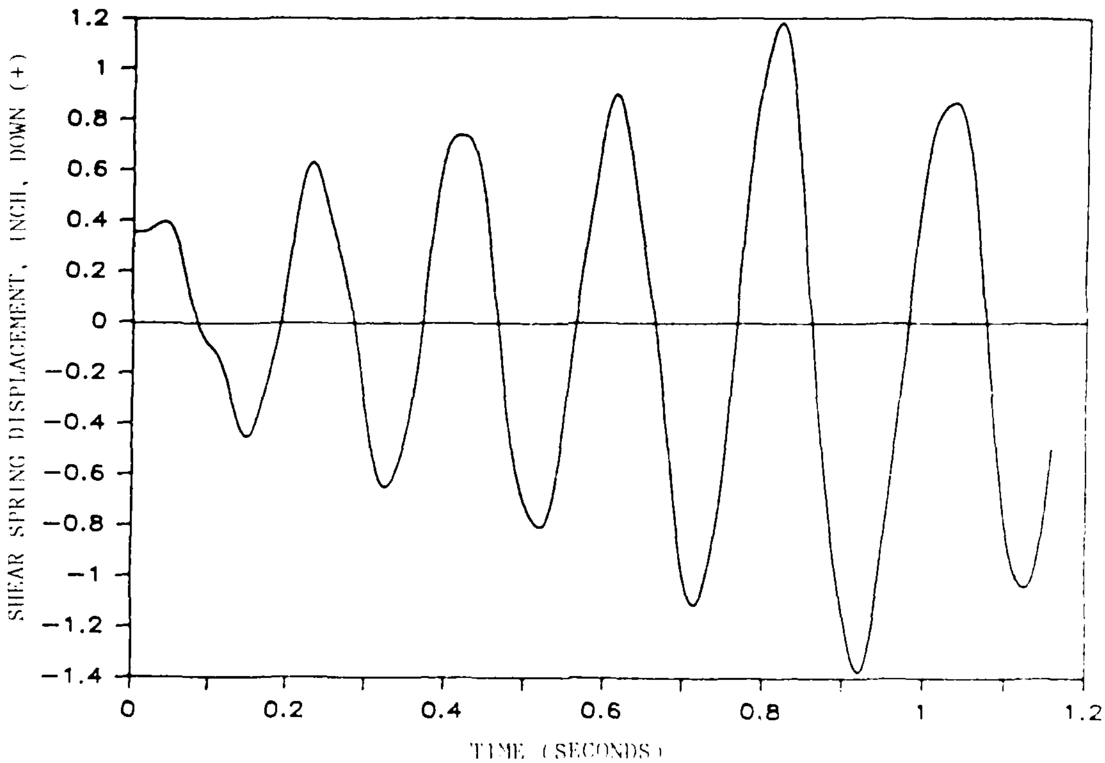


Figure 17. Shear spring displacement for Vibro 1800.

CONCLUSIONS

Field Tests

Valuable information was gained from the field tests. Experience gained from the setup and performance of the tests will help improve the design of future experiments.

The extremely dense sand conditions found in the test area limited both the type and quantity of data collected. However, the data that were collected were satisfactory for comparison with the computer model predictions.

Computer Simulation

The wave equation appears to offer a feasible method of analyzing vibratory pile driving. It was found that a proper simulation of the vibratory driver is critical to predicting correct results. Most notable is proper modeling of the isolation spring stiffness.

Interpretation of the field results with the VIBEWAVE program has helped to clarify areas where more work will be required. To improve and refine the predictive method, it is necessary to collect data from pile driven to greater depths. Using the vibratory pile driving record in conjunction with the computer model, it appears that a practical solution to predicting the driveability and bearing capacity of vibratory driven piles is possible.

RECOMMENDATIONS

Based on the findings of this preliminary study, it is possible to define and make recommendations on the areas that need to be researched before a valid understanding of the vibratory pile driving process can be reached. The following recommendations are made:

Vibratory Pile Driving Using VIBEWAVE:

1. Evaluate the effects of different driving frequencies and amplitudes, eccentric moments (which are determined by the eccentric weights and rotating arms), and properties of the other components for the various types of vibratory drivers.

2. Evaluate the performance of other types (apart from Foster's) of vibratory drivers in order to determine if the mechanism of driving is the same. It may be that some drivers depend more on the suspended weight for increased efficiency while others might rely more on the magnitude of the eccentric moment or the driving frequency.

3. Manufacturers of vibratory drivers should consider including information regarding the eccentric weights (including the gears), and the eccentricity and the stiffness of the isolation spring and/or the suspension system if any, in their brochures.

Improvement of the VIBEWAVE Program

To more accurately model the vibratory hammer-soil-pile system, it may be necessary to modify the program to accept a nonlinear spring, especially for the more flexible elements. For example, the isolation spring may be somewhat linear in tension, but it is not so in compression. It may be necessary to develop a temperature-dependent pile driving model to properly model the effects of the high temperatures observed in the tests.

Soil-Pile Interaction During Vibratory Driving

1. Determine the effects of grain size and shape of coarse-grained soil on vibratory driving.

2. Compare the pile capacity of a vibratory driven pile and an impact driven pile.

3. Determine the effects of temperature in the driving on soil resistance under dry and wet conditions.

4. Define the effects of the water table on driving.

5. Determine the amount of resistance (or reduction in static resistance) at the side and the pile point while driving. This will require driving deeper piles and monitoring the stresses along the entire length of the pile while driving.

Design of a More Efficient Vibratory Hammer

Consider designing a system with a variable driving frequency and variable isolation spring stiffness, as well as variable eccentric weights and rotating moment arms.

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32 Alternate energy source (geothermal power, photovoltaic power systems, solar systems, wind systems, energy storage systems)
33 Site data and systems integration (energy resource data, energy consumption data, integrating energy systems)
34 **ENVIRONMENTAL PROTECTION**
35 Solid waste management
36 Hazardous/toxic materials management
37 Wastewater management and sanitary engineering
38 Oil pollution removal and recovery
39 Air pollution
44 **OCEAN ENGINEERING**
45 Seafloor soils and foundations
46 Seafloor construction systems and operations (including diver and manipulator tools)
47 Undersea structures and materials
48 Anchors and moorings
49 Undersea power systems, electromechanical cables, and connectors
50 Pressure vessel facilities
51 Physical environment (including site surveying)
52 Ocean based concrete structures
54 Undersea cable dynamics

TYPES OF DOCUMENTS

85 Techdata Sheets
86 Technical Reports and Technical Notes
82 NCEL Guides & Abstracts
None-- remove my name
83 Table of Contents & Index to TDS
91 Physical Security

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